American Journal of Public Health
and THE NATION'S HEALTH

Volume 31 July, 1941 Number 7

Composition of Diesel Engine Exhaust Gas*

H. H. SCHRENK, PH.D., F.A.P.H.A., AND L. B. BERGER

Chief Chemist, Health Division, Bureau of Mines; and Associate Chemist, Gas and Dust Section, Central Experiment Station, Bureau of Mines, Pittsburgh, Pa.

PROBLEMS requiring the assistance of industrial hygienists have been associated with virtually every major industrial advancement. The automobile introduced many industrial hygiene problems not only in its manufacture but also in fields associated with its use, such as the ventilation of vehicular tunnels and the production and utilization of gasoline and lead tetraethyl. Mechanical refrigeration was accompanied by hazards from toxic gases and vapors. Innumerable examples could be given, but the above are enough to indicate the significant rôle of the industrial hygienist in our industrial progress. It is becoming more and more an accepted policy of industry that the effects of new products and developments on the workers and users should be known before their widespread application.

It has been suggested that Diesel engines could be used safely underground, based upon a comparison with gasoline engines, and assuming that (1) the carbon monoxide content of the Diesel exhaust is always low, and that (2) fire and explosion hazards from Diesel fuel are minimized because of its low volatility. In these respects Diesel engines appear less hazardous than gasoline engines whose use underground has been discouraged by the Bureau of Mines and other organizations interested in safety and mining. Therefore, owing to the increased interest in the possible use of Diesel engines as the source of power for haulage equipment in mines and tunnels in this country, and in line with the policy of studying the hazards associated with new developments and applications, the Bureau of Mines has initiated a study of the hazards involved in the use of Diesel engines underground.

---

* Contribution from the Central Experiment Station, Bureau of Mines, Pittsburgh, Pa.

Published by permission of the Director, Bureau of Mines, U. S. Department of the Interior, Washington, D. C.

Read at a Joint Session of the Engineering and Industrial Hygiene Sections of the American Public Health Association at the Sixty-ninth Annual Meeting in Detroit, Mich., October 9, 1940.

The main phase of this study to date has dealt with the composition of the exhaust gas, knowledge of which is essential to the safe use of Diesel engines underground or in confined spaces. Such information also may be valuable in establishing a basis for the ventilation of vehicular tunnels, as the requirements for Diesel engines may differ from those of gasoline engines. This paper does not include information based upon underground use.

COMPARISON OF OPERATING PRINCIPLES OF GASOLINE AND DIESEL ENGINES

Before proceeding with presentation of the details of this investigation it may be well to consider some of the basic differences in the operating principles of gasoline engines and Diesel engines:

In conventional gasoline engines, equipped with carburetor and spark-ignition, the fuel is atomized, vaporized, and mixed with air in the carburetor. The gasoline-air mixture is then drawn into the cylinders, compressed, and ignited by an electric spark. The power output of the engine is regulated by the quantity of this mixture admitted to the cylinders through a throttling device interposed between the carburetor and the cylinders.

In the Diesel, or compression-ignition engine, fuel and air are mixed directly in the cylinders. An essentially constant volume of air is drawn into the cylinders and compressed. Near the end of the compression stroke, fuel under high pressure is sprayed into the air, which, because it has been compressed, is at high enough temperature to cause spontaneous ignition of the fuel. The power output of Diesel engines is controlled by regulation of the quantity of fuel injected into the cylinders by a fuel pump capable of delivering varying quantities of fuel at high pressure.

It is evident that the ratio of fuel to air in the mixture supplied to the gasoline engine must be restricted to proportions that are within the inflammable or explosive limits of gasoline-air mixtures. The range of ratios of fuel to air within which a gasoline engine operates is therefore limited as compared to the fuel-air ratios obtained in Diesel engines, where air supply is essentially constant and fuel quantity is varied to meet power-output demand.

Furthermore, to obtain satisfactory

TABLE 1

Description of Engines Tested

Designation of engine	*A*	*B*
Type	4-stroke cycle	4-stroke cycle
Number of cylinders	4	4
Cylinder bore ... inches	4¼	4
Piston stroke ... inches	5½	4½
Piston displacement ... cubic inches	312.1	226.2
Maximum rated speed ... r.p.m.	1,400	2,600
Maximum rated brake horse power (without accessories)	44	70
Fuel pump	Individual pump for each cylinder; fuel delivery controlled by pump plunger by-pass	Individual pump for each cylinder; fuel delivery controlled by pump plunger by-pass
Type of injection valve	Single-hole orifice; flat-faced valve seat	Circumferential orifice (pintle nozzle); conical valve seat
Opening pressure of injection valve discharging into air at atmospheric pressure lb. per sq. in.	1,500	1,650
Combustion system	Cylindrical precombustion chamber with cone-shaped ends	Spherical turbulence or air-swirl chamber
Cooling system	Positive circulation, thermostatically controlled	Positive circulation, thermostatically controlled

performance with gasoline engines, the fuel-air ratio is adjusted so that there is too little air in the mixture for complete combustion of the fuel, thus producing considerable quantities of carbon monoxide. In contrast, Diesel engines can be operated at fuel-air ratios such that an excess of air is always present, and combustion proceeds much more nearly toward completeness.

TEST EQUIPMENT AND PROCEDURE

Engines and Dynamometer

Two standard, commercial Diesel engines have been tested. Each was mounted in a "power unit," including radiator, fan, clutch, fuel system, and starting mechanism. Each unit was coupled to an electric dynamometer to permit operation at various speeds and power outputs. The engines, designated "A" and "B," are described in Table 1.

The engines were adjusted in accordance with the recommendations of the manufacturers, except in the tests in which the adjustment of the fuel pump was altered to permit an increase in fuel injection. The report does not include data on the effect of such factors as excessive wear, improper atomization of fuel, or other maladjustments that might have significant effects on the composition of the exhaust gas.

Fuel

The chemical and physical properties of the fuel were as follows:

Flash point (P.M.C.C.)	°F.	Above	200
Water and sediment		Trace	
Viscosity, S.U. at 100° F.	sec.		48
Carbon residue		Trace	
Ash		do	
Gravity	°A.P.I.		38.8
Pour point (upper)	° F.		50
Cetane number (knockmeter delay method)			78
Sulfur	per cent	Trace	
Hydrogen	do		14.0
Carbon	do		86.0
Nitrogen	do		0
B.t.u. per lb.			19,910

Test Procedure

The engines were new when received and were run for 100 hours at various speeds and loads before any tests were made. For each test the engine was operated for 1 hour at the desired speed and load conditions. During the last 15 minutes of this period samples of exhaust gas were collected, and a final measurement was made of fuel consumption.

Gas Sampling and Analysis

Constituents of Diesel exhaust gas that may create harmful or objectionable atmospheres are carbon monoxide, oxides of nitrogen, carbon dioxide, aldehydes, soot, and oxides of sulfur (if the fuel contains sulfur). The exhaust also contains water vapor, oxygen, and nitrogen; and under some conditions, hydrogen and methane; and trace amounts of other organic compounds.

Arrangements for collecting exhaust-gas samples are shown diagrammatically in Figure 1. Samples for determination of carbon dioxide, oxygen, carbon monoxide, methane, hydrogen, and nitrogen were collected from a metal tube inserted into the exhaust stack a short distance from the outlet of the manifold. A continuous stream of gas was drawn through this tube during sampling; a water seal was included in the sampling line as a precaution against contamination of the samples by air. An air-cooled condenser in this sampling line freed the gas stream of water that otherwise would have collected in the sample bottles. Samples for determination of carbon dioxide, oxygen, methane, hydrogen, and nitrogen were collected by mercury displacement. Samples for determination of carbon monoxide only were collected by water displacement. Samples for determination of aldehydes and oxides of nitrogen were collected (in evacuated bottles) through short lengths of glass tubing inserted into the exhaust stack through

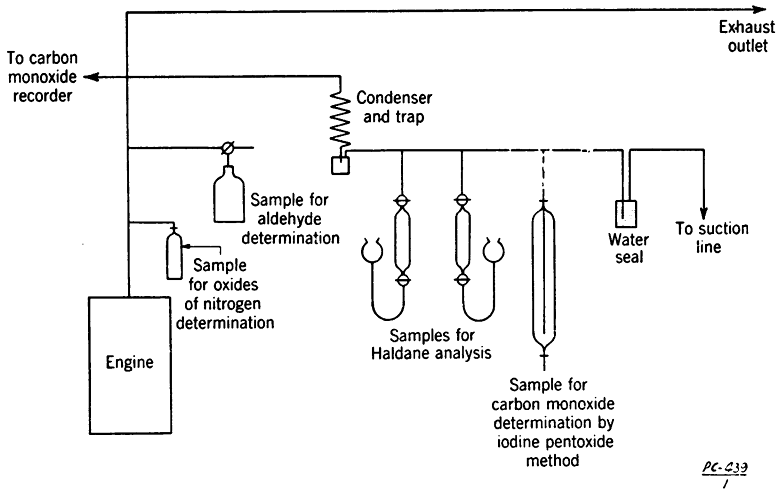

FIGURE 1—Diagrammatic sketch of arrangements for sampling exhaust gas

asbestos-packed stuffing boxes. The exhaust pipe of the engine was extended approximately 9 ft. beyond the sampling points before it terminated outdoors. This precaution is necessary in sampling the exhaust gases of an internal-combustion engine, as the pulsations in gas flow cause air to be drawn into the pipe between exhaust impulses for a considerable distance from the discharge end.

Carbon monoxide—Carbon monoxide was determined by the iodine pentoxide method when less than 0.5 per cent was present. If it exceeded this amount it was determined in a Bureau of Mines type laboratory Orsat apparatus by absorption in a mixture of cuprous sulfate, beta naphthol, and sulfuric acid.

Oxides of nitrogen—Oxides of nitrogen were determined by the phenoldisulfonic acid method.

Aldehydes—Aldehydes were determined colorimetrically with the Schiff-Elvove reagent, which produces color with practically all aldehydes, using formaldehyde as a standard.

Carbon dioxide, oxygen, methane, hydrogen, and nitrogen—These gases were determined in a Bureau of Mines type Haldane gas-analysis apparatus, except in certain samples in which the carbon monoxide content necessitated analysis in the Orsat apparatus.

RESULTS OF TESTS

The results of the tests are presented in the following tables and figures.

Table 2 shows representative data. The complete data have been published elsewhere [1] and are not presented here because of lack of space. The constituents of the exhaust that are of particular interest from the hygienic standpoint are carbon monoxide, oxides of nitrogen, carbon dioxide, oxygen, aldehydes, soot or smoke, and oxides of sulfur if the fuel contains significant amounts of sulfur.

Effect of Fuel-Air Ratio on Composition of Exhaust Gas

The effect of fuel-air ratio on exhaust gases from internal-combustion engines is extremely important from the standpoint of hygienic atmospheric conditions. Figure 2 shows the relationship of composition of exhaust gas to fuel-air ratios ranging from about 0.01 to 0.094 lb. of fuel per lb. of air. At a fuel-air ratio of 0.0679 there would be, theoretically, with the fuel used in these

TABLE 2

Representative test data and results—Engine B at approximately 1,400 r.p.m.

Test No. →	*B-13*	*B-14*	*B-15*	*B-16*	*B-12*	*B-70*	*B-72*	*B-69*
Net power output, b.h.p.	0 [1]	8.8	17.5	26.4	37.8	40.2	41.0	40.6
Fuel consumption, lb. per hr.	4.56	6.89	9.56	12.45	18.12	21.29	24.41	29.63
Volume of exhaust gas, cu. ft. per hr. [2]	4,500	4,460	4,180	4,050	3,950	3,700	3,650	4,050
Fuel-air ratio, lb. per lb.	0.013	0.020	0.029	0.039	0.056	0.070	0.084	0.094
Composition of exhaust gas, per cent by volume [3]								
CO_2	2.74	4.19	6.22	8.36	12.40	13.8	12.1	10.2
O_2	17.14	15.13	12.20	9.26	3.44	0.8	0.3	0.3
CO [4]	0.041	0.028	0.024	0.027	0.058	0.7	3.3	6.0
H_2	— [5]	—	—	—	—	0.1	1.3	3.0
CH_4	— [5]	—	—	—	0.03	0.1	0.3	0.4
N_2	80.08	80.65	81.56	82.35	84.07	84.5	82.7	80.1
Oxides of nitrogen, p.p.m. by volume [6]	167	267	378	448	364	346	277	186
Aldehydes, p.p.m., by volume [7]	4	1	1	1	4	1	2	0

[1] Minimum power output. Power output of engine consumed in mechanical losses and in driving accessories.

[2] Calculated as dry gas at 60° F. and 29.92 in. of mercury pressure.

[3] Calculated on a dry basis. Analyses in Bureau of Mines-type Haldane or Orsat apparatus.

[4] Values expressed to three decimal places were determined by the iodine pentoxide method; in calculating nitrogen by difference these values were expressed to nearest unit in second decimal place to conform with results of Haldane analysis. Carbon monoxide determined by combustion or absorption in tests B-70, B-72, and B-69.

[5] Dash indicates none detectable by analytical method used.

[6] As nitrogen peroxide, NO_2; not included in sum of percentages of other gases.

[7] As formaldehyde; not included in sum of percentages of other gases.

tests, just enough oxygen to burn completely all the fuel present, and this ratio is designated as the "chemically correct mixture." Thus, the fuel-air ratios studied included those in which air was present in considerable excess as well as those with insufficient air for complete combustion. The engines as received from the manufacturers were adjusted so that the maximum fuel-air ratio for engine A was 0.042 and for engine B 0.058 lb. per lb. The excess air present under these conditions was 61 and 17 per cent, respectively. It was necessary to change the manufacturer's adjustment of the fuel pump to obtain higher ratios at full throttle, and this was done with engine B. The maximum ratio studied was 0.094, and at this ratio only 70 per cent of the air required for complete combustion was present.

It will be observed from Figure 2 that, regardless of engine speed, the oxygen content of the exhaust decreased regularly to produce virtually a linear relationship up to a fuel-air ratio of 0.06. The carbon dioxide increased regularly and a similar linear relationship was produced up to about the same fuel-air ratio. These relationships illustrate the changes in the proportions of the reacting sub-

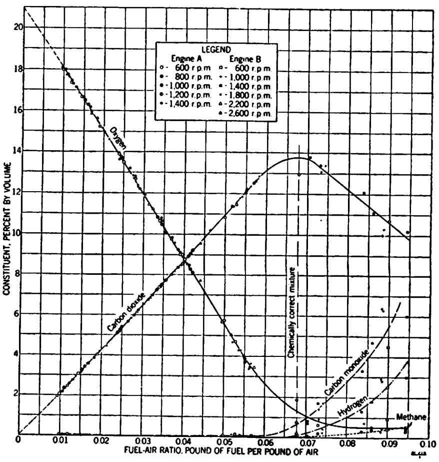

FIGURE 2—Relationship of composition of exhaust gas to fuel-air ratio

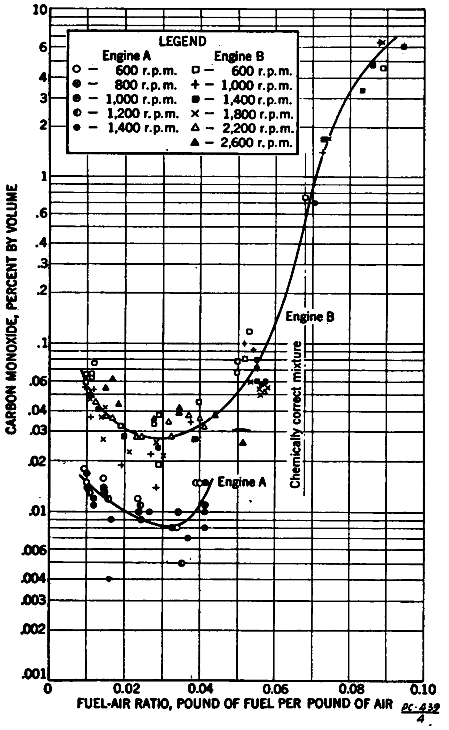

FIGURE 3—Relationship of carbon monoxide concentration in exhaust gas to fuel-air ratio

stances, fuel and air, as the power output of the engine, and consequently the fuel-air ratio, was increased. The concentration of carbon monoxide showed a marked increase as the fuel-air ratio approached the chemically correct mixture; and hydrogen and methane, which were not detected at lower fuel-air ratios, were found when the fuel-air ratio exceeded the chemically correct mixture.

Carbon Monoxide

For more complete and comprehensive presentation, the data for carbon monoxide have been replotted in Figure 3 with carbon monoxide on a logarithmic scale in relation to fuel-air ratio on a linear scale. It is evident that the concentration of carbon monoxide can vary over a wide range, depending on fuel-air ratio. Within the range of fuel-air ratios for which the engines were adjusted by their manufacturers the carbon monoxide content of the exhaust of engine A did not exceed 0.02 per cent and of engine B, 0.12 per cent. However, in tests with this adjustment altered, as the chemically correct mixture was approached from the lean side,* the concentration of carbon monoxide increased rapidly, and the effect was even greater when the chemically correct mixture was exceeded on the rich side * and concentrations of carbon monoxide comparable to those found in exhaust gases from gasoline engines were observed. Engine speed apparently had no pronounced effect on the concentration of carbon monoxide, although some slight variations that may be attributable to speed are noticeable in Figure 3.

If any advantages from the standpoint of carbon monoxide in the exhaust gas are to be gained from the use of the Diesel engine as compared to the gasoline engine, operation must be confined to fuel-air ratios less than the chemically correct mixture. Fortunately the characteristics of the Diesel engine are such that it can be operated near its maximum power output at such fuel-air ratios (see Figure 6). Thus, it is possible to control to a large extent the carbon monoxide hazard with proper engine adjustment without significant sacrifice of power output. Although carbon monoxide can be largely controlled in this manner the hazard should not be dismissed lightly nor should it be overlooked that ventilation is required.

Oxides of Nitrogen

The maximum concentration of oxides of nitrogen (expressed as equivalent nitrogen peroxide, NO_2) observed in the exhausts of engines A and B were respectively 440 and 676 p.p.m. of exhaust

---

* Fuel-air ratios less than the chemically correct mixture are referred to as being "on the lean side," and ratios greater than the chemically correct as being "on the rich side."

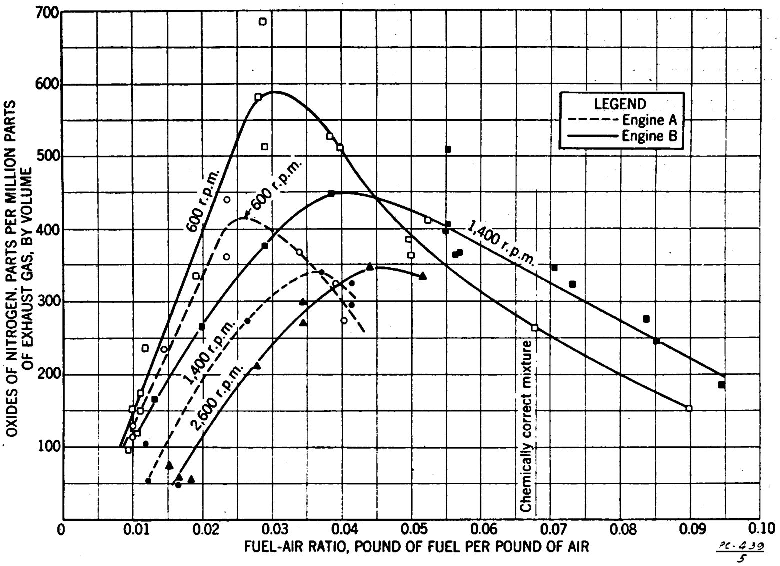

FIGURE 4—Relationship of concentration of oxides of nitrogen in exhaust gas to fuel-air ratio

gas, by volume, concentrations that obviously are of hygienic significance.

Figure 4 shows the relationship of concentration of oxides of nitrogen to fuel-air ratio. The concentration of oxides of nitrogen reached a maximum at intermediate fuel-air ratios. The maximum attained depended on engine design and speed, the value decreasing with increase in speed, with a tendency to shift to higher fuel-air ratios with increase in speed. The occurrence of a maximum in the concentration of oxides of nitrogen at intermediate fuel-air ratios may be attributable to a combination of the effects of the temperature of combustion and of the concentration of oxygen present during combustion. From the lowest fuel-air ratios to the intermediate values, the temperature of combustion increases, and predominates in the formation of oxides of nitrogen. From the intermediate to the higher fuel-air ratios, the diminishing concentration of oxygen would tend to inhibit their formation, and appears to be the predominating factor controlling their production in this range of fuel-air ratios.

Consideration of the possible effects of such factors on the production of oxides of nitrogen indicates that the concentration of these compounds in the exhaust might be expected to vary appreciably with different engines and operating conditions.

TABLE 3

Relationship between aldehyde content of exhaust gas and odor intensity and irritating effects

Aldehyde Content, Range of Concentrations, Parts per Million	*Odor Intensity*	*Irritating Effects*
0 to 10	Faint (weak odor, readily perceptible)	None to slight
10 to 50	Easily noticeable (moderate odor)	Slight (just perceptible)
50 to 100	Easily noticeable to strong odor	Moderate to strong (midway between just perceptible and discomforting)
100 and over	Very strong (intense effect)	Intolerable (exceedingly painful)

With concentrations of oxides of nitrogen of the order found, dilution of the exhaust gas is necessary for hygienic atmospheric conditions.

Aldehydes

The well known characteristic odor of Diesel exhaust is undoubtedly caused by partly oxidized organic substances, and possibly products of thermal decomposition, and it seems probable that aldehydes constitute a large part of these substances.

The concentration of aldehydes ranged from 0 to 5 p.p.m. in the exhaust from engine A and from 0 to 31 p.p.m. in the exhaust of engine B.

To ascertain the significance of these results, limited observations were made of the odor intensity and irritating effects of the exhaust when samples were taken for analysis. A correlation of these data is presented in Table 3. This table was prepared from 136 observations by 11 observers during some special experiments in which the range of aldehyde concentration was considerably broader than in the tests covered by this report. The response given under odor intensity or irritation represents the majority of observations for each particular range of concentration. As might be expected, there was considerable spread in the estimates of individuals. Nevertheless, there appears to be a correlation between odor and irritation of the exhaust gas and aldehyde content. However, it is emphasized that the number of observations and observers was limited and that other unidentified organic compounds may have been present and contributed to both odor and irritation. Although aldehydes in the concentrations found do not appear to present a health hazard when compared to the other toxic gases present, nevertheless they constitute a significant nuisance worthy of considerably more study.

Figure 5 shows the general trend in

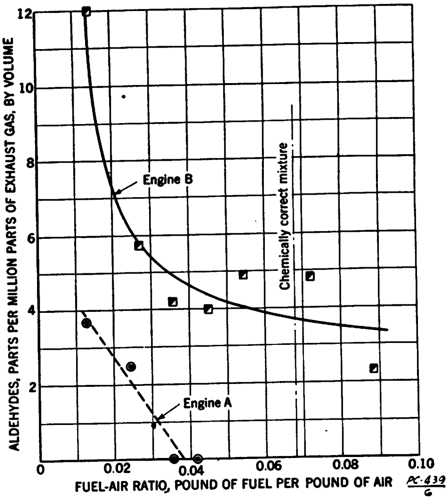

FIGURE 5—Trend of aldehyde concentration in exhaust gas with fuel-air ratio

the relationship of the aldehyde content of the exhaust gas to fuel-air ratio. The results indicate definite increase in concentration of aldehydes at the low fuel-air ratios.

Because of considerable variation in concentration of aldehyde in comparable tests, the discussion of the effect of engine speed on this constituent does not appear warranted. However, the data indicated the possibility that there was a tendency toward a decrease in aldehydes with increase in speed. As in the case of oxides of nitrogen, it appears probable also that engine design and operating conditions will have a marked effect on production of aldehydes.

Carbon Dioxide

The concentration of carbon dioxide in the exhaust from the two engines was between 2 and 13 per cent. Such concentrations may be expected from all Diesel engines, although the maximum and minimum concentrations for any given engine will depend on its adjustment. As an atmosphere containing more than 1 per cent carbon dioxide is not considered a satisfactory working environment, this gas must be considered in estimating the amount of ventilation required for safe use of Diesel engines underground.

Oxygen

The oxygen concentration in the exhaust gas is an indication of the oxygen consumed by combustion in the engine, and ventilation must be provided to replace the oxygen consumed so as to maintain an oxygen concentration greater than 19 per cent, the minimum considered permissible.

Oxides of Sulfur

Data on oxides of sulfur were not obtained because the fuel used was essentially sulfur-free. Obviously, if the fuel contains significant amounts of sulfur, it would be necessary to give consideration to the oxides of sulfur. Calculations indicate that a fuel containing 0.5 per cent sulfur would produce about 330 p.p.m. sulfur dioxide at the chemically correct fuel-air ratio. As this concentration, under certain conditions, might be the controlling factor in ventilation it is possible that the sulfur in the fuel should not exceed 0.2 to 0.3 per cent. More data are needed to establish this value definitely.

Smoke

The appearance of the exhaust was observed to obtain information on the tendency of the engines to produce smoke. When either engine was operated at its minimum load, particularly at low speed, a light blue haze was observed. This haze was present when either engine was idled, and was noticeably denser immediately after a cold engine was started. It was generally faint and could be distinguished only in reflected light. When either engine was operated under load, no haze was evident. In tests with engine B in which the adjustment of the fuel pump was altered to permit injection of additional fuel at full throttle, the appearance of the exhaust ranged from light gray at fuel-air ratios just greater than chemically correct to black at higher fuel-air ratios.

In addition to these visual estimates of smoke in the exhaust, qualitative tests always showed the presence of soot or free carbon in the exhaust of both engines, and calculations [2] applied to the test data indicated varying concentrations of free carbon in the exhaust of engine B throughout the wide range of fuel-air ratios (approximately 0.01 to 0.09) covered in tests with this engine. These calculations showed a definite relationship between fuel-air ratio and concentration of free carbon in the exhaust and also conformed with the visual estimates of smoke density, exhibiting a minimum at fuel-air ratios of from approximately 0.025 to 0.04, and a maximum at the highest ratio studied. Free carbon appears to be a normal constituent of Diesel exhaust throughout the entire operating range, although by far the most dense and objectionable smoke is produced by operation at fuel-air ratios where there is little or no excess air for combustion, and this is a condition that can be controlled by restricting operation to a proper range of fuel-air ratios.

Smoke production also may be caused by other conditions, including operation with the engine below proper temperature, faulty injection of fuel spray, excessive consumption of lubricating oil, and possibly use of low-grade fuel.

Relation of Power Output to Fuel-Air Ratio

Figure 6 shows the relationship of power output at constant speed to fuel-air ratio and illustrates a relationship characteristic of Diesel engines, in common with other types of internal-combustion engines, namely, that power output increases with fuel-air ratio until a maximum is reached on the rich side. Data illustrating this relationship were obtained in tests of engine B at 1,400 r.p.m.; a similar relationship was observed in all tests covering a comparable range of fuel-air ratios. If the tests had been extended to include higher fuel-air ratios, the power output in this range would have decreased from the maximum shown in Figure 6.

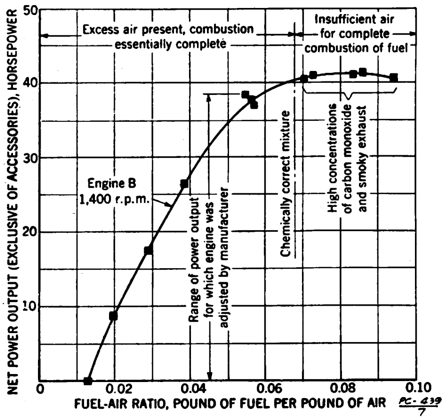

FIGURE 6—Relationship of power output to fuel-air ratio at 1,400 r.p.m. in tests with engine B

At constant speed and atmospheric conditions the weight of air drawn into a Diesel engine is approximately the same throughout the range of power output, and when combustion is essentially complete power output increases with the rate at which fuel is injected. Therefore, power output increases with fuel-air ratio in the range of essentially complete combustion.

In addition to the fact that the power output increased only slightly for fuel-air ratios above the chemically correct mixture it was noted also that this slight increase was obtained by a very large increase in fuel consumption. In other words, it is not economical to attempt to obtain an increased power output by operating at fuel-air ratios in excess of the chemically correct mixture. This point is emphasized because, as stated previously, it is necessary, in order to prevent large increases in the production of carbon monoxide, to regulate the fuel pump so that excessive fuel-air ratios cannot be attained. Such regulation of the fuel injection also tends to reduce excessive smoke formation, and it is significant that both carbon monoxide and smoke production can be largely controlled without materially affecting the power output of the engine.

Relation of Volume of Exhaust Gas to Engine Speed

The volume of exhaust gas produced is a necessary factor in calculating ventilation requirements. In this investigation the hourly production of exhaust gas was calculated from the rate of fuel consumption and from material balances between the constituents of the fuel and of the exhaust gas.[1] Figure 7 shows the volume of dry exhaust gas produced per hour by the engines in relation to speed. Two curves are included for each engine, one for minimum power output (accessories only), and the other for maximum rated power output. Piston displacement on the intake stroke is shown because the volume of air drawn into the engine is the principal factor in determining the volume of exhaust gases produced. The curves in Figure 7 show that at any given speed the volume of dry exhaust decreased slightly as the power output of the engine increased. Part of this decrease is a result of expressing the gas volume on a dry basis and not including the calculated volume of water vapor formed in combustion. In addition, part of the decrease may be due to changes in volumetric efficiency.

The piston displacement on the intake stroke shown in Figure 7 represents the maximum possible volume of air that can be taken into the engine. As the volume of dry exhaust gas is always less than the volume of air taken into the engine, in lieu of actual test data, the piston displacement on the intake stroke could be used as an approximation of the volume of dry exhaust gas.

The volume of exhaust gas produced per unit time may be used as a basis for estimating the quantity of ventilating air required in locations such as mines or tunnels where adequate ventilation is imperative if Diesel engines are to be used safely. This estimate of ventilation is based upon dilution with air of the toxic constituents of the exhaust to concentrations considered permissible from the hygienic standpoint. The methods of calculation used in arriving at this estimate of ventilation have been described in detail in another publication.[1] It is emphasized, however, that such calculation produces a minimum value and is based upon the assumption that air of normal composition will be supplied for ventilation. In practical applications it appears that a margin of safety is desirable, and for this reason it is advisable to furnish an excess of ventilating air rather than to adhere to the minimum indicated by calculation. Further study of Diesel engines in the laboratory and under actual operating conditions should furnish a basis for deciding the magnitude of this margin of safety. It is possible that when more experience is gained, some empirical method may be found suitable for calculating ventilation required for any particular engine, but until such broad experience is gained, the calculation of basic ventilation requirements from tests of the type described appears to be the most rational approach to the problem.

DISCUSSION

As both laboratory results and practical experience have been limited, broad generalizations and final recommendations cannot be made; however, the information obtained to date indicates certain trends that should be of interest to the industrial hygienist. The statement is frequently seen that the amount of carbon monoxide in the exhaust of Diesel engines is negligible, with no mention of the other constituents. It is not believed that such statements are justifiable; and, even though no carbon monoxide were present, ventilation would be required to dilute the carbon dioxide produced and to maintain the oxygen content of the atmosphere above 19 per cent. The emphasis on carbon monoxide is probably due to the fact that it is associated with internal combustion engines, and from a

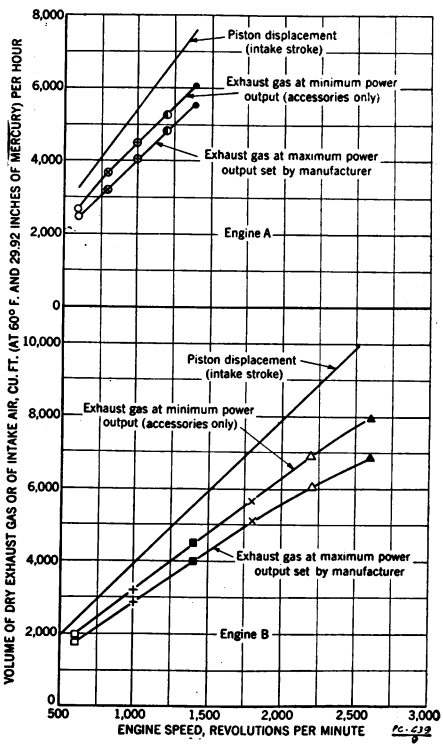

FIGURE 7—Relationship of volume of exhaust gas to engine speed at minimum and maximum power outputs

theoretical standpoint it is probably the most significant constituent of Diesel exhaust gas owing to the fact that the amounts present may vary over an extremely wide range. However, the amounts present can be largely controlled, without significantly sacrificing power output, by operating in a suitable range of fuel-air ratios. Even under these conditions some carbon monoxide will be produced, and ventilation will be required for dilution. Provisions to prevent excessively high fuel-air ratios should be provided in the design of the engine as this is of extreme importance in the control of the carbon monoxide and smoke.

Oxides of nitrogen also occur in amounts that would be dangerous to health, and dilution of these gases is essential in preventing the production of unhygienic atmospheric conditions.

From a limited observation of Diesel locomotives underground, it seems possible to conclude that the ventilation required to dilute the carbon monoxide, oxides of nitrogen, and carbon dioxide to permissible concentrations might not be adequate to eliminate a nuisance from the smoke and odor of the exhaust gases. In other words, even though ventilation suffices to dilute the toxic gases to a permissible limit, additional ventilation may be necessary to prevent complaints from smoke and odors and irritation from the exhaust gases.

In regard to smoke, it might be pointed out that controlling the fuel-air ratio appears to have a very beneficial effect in preventing the occurrence of significant amounts of unburned carbon or smoke in the exhaust gases. For example, the dense black smoke that is frequently associated with Diesel exhaust was observed only when the engine was operated at fuel-air ratios exceeding the chemically correct mixture.

The fact that certain harmful and objectionable constituents of Diesel exhaust gas can be largely controlled by proper design of Diesel engines is interesting, in that it is in line with the recent trend of giving consideration to the industrial hygiene hazards associated with new developments.

SUMMARY

The composition of the exhaust gas of two commercial Diesel engines in proper mechanical condition was determined at different speeds and power outputs for fuel-air ratios ranging from approximately 0.01 to 0.09 lb. per lb. The constituents of the exhaust were carbon monoxide, oxides of nitrogen, carbon dioxide, aldehydes, soot, oxygen, nitrogen, water vapor, and under some conditions hydrogen and methane or other hydrocarbons. Oxides of sulfur would be present if the fuel contains sulfur. Carbon monoxide, carbon dioxide, and oxides of nitrogen were present in concentrations that are considered harmful to breathe. Under some conditions objectionable amounts of aldehydes and smoke may be produced.

The fuel-air ratio was found to have a marked effect on the production of carbon monoxide. When the engines were operated within the range for which they were rated and adjusted by the manufacturers, the maximum concentration of carbon monoxide in the exhaust from one engine was 0.02 per cent and in the other 0.12 per cent. However, by changing the adjustment limiting the quantity of fuel injected at full throttle so that fuel was injected in excess of that which could be burned completely by the air taken into the engine, the carbon monoxide was increased markedly, and concentrations of the order of those found in exhaust from gasoline engines were produced. Moreover, under these conditions, a large amount of smoke was produced. It is significant that the production of carbon monoxide and smoke can be largely controlled by the proper adjustment of the fuel-air ratio without a significant sacrifice of power output of the engine at full throttle.

Although experience is limited, the results indicate the importance of controlling the fuel-air ratio and also that Diesel engines should not be operated

underground unless ample ventilation is provided.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the advice and guidance given by D. Harrington, chief, Health and Safety Branch; A. C. Fieldner, chief, Technologic Branch; and W. J. Huff, consulting explosives chemist, Explosives Division, Bureau of Mines.

The Health Division and Explosives Division are coöperating in this investigation, and the authors acknowledge the valuable assistance of J. C. Holtz, gas engineer, and M. A. Elliott, associate gas engineer, Explosives Division. The authors are indebted also to H. A. Watson, A. P. Rowles, R. L. Beatty, B. D. Polis, R. E. Kennedy, and C. K. White, of the Bureau of Mines, who participated in various phases of the work. Acknowledgment is given to the National Bureau of Standards and the Coal Analysis Laboratory of the Bureau of Mines for furnishing data on the properties of the fuel.

REFERENCES

1. Holtz, J. C., Berger, L. B., Elliott, M. A., and Schrenk, H. H. Diesel Engines Underground. I—Composition of Exhaust Gas from Engines in Proper Mechanical Condition. *Bu. Mines Rep. Investigations 3508*, 1940, 48 pp.
2. Holtz, J. C., and Elliott, M. A. *The Significance of Diesel Exhaust Gas Analysis.* Presented at June 1940 Meeting Oil and Gas Power Div. A.S.M.E. 8 pp.